

PERFORMANCE OF THE AIRS PULSE TUBE COOLERS AND INSTRUMENT—A FIRST YEAR IN SPACE

R.G. Ross, Jr. and J.I. Rodriguez

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

ABSTRACT

Launched on NASA's Aqua platform on May 4, 2002, JPL's Atmospheric Infrared Sounder (AIRS) instrument has completed a successful first year in space and captured a number of important lessons. AIRS is designed to make precision measurements of air temperature over the surface of the Earth and uses a redundant pair of TRW 55 K pulse tube cryocoolers to cool its sensitive IR focal plane. Soon after the instrument went cold, contamination of cryogenic surfaces led to increased cooler loads and the need for decontamination cycles. In addition, single event transients occurred while passing through the South Atlantic Anomaly (SAA) necessitating corrective actions. In November 2002 the fundamental operating strategy of the AIRS instrument was changed from the original strategy of running a single cooler and having the second cooler as a non-operating backup. Instead, based on a new system-level reliability analysis, both coolers began operation simultaneously. This change resolved the contamination and SAA driven interruptions and has enabled unprecedented levels of continuous science measurements. A review of the AIRS instrument cryogenic performance over the past year is presented including its contamination buildup and interrupt history. The reliability analysis conducted to justify two-cooler operation is also reviewed.

INTRODUCTION

The objective of the AIRS instrument is to provide new and more accurate global air temperature data for application to climate studies and weather prediction. The technical foundation of the AIRS instrument is a precisely calibrated, high spectral resolution grating spectrometer operating between 3.7 to 15.4 μm . The cryogenically cooled spectrometer uses a pair of TRW (now Northrup Grumman Space Technologies) 55 K pulse tube cryocoolers to cool the HgCdTe focal plane to 58 K [1]. The ambient portion of the instrument contains the high power components including the instrument electronics and the cryocooler compressors and their electronics. The waste heat from these assemblies is removed by means of a spacecraft-provided heat rejection system (HRS) that utilizes variable conductance heat pipes and space-viewing radiators.

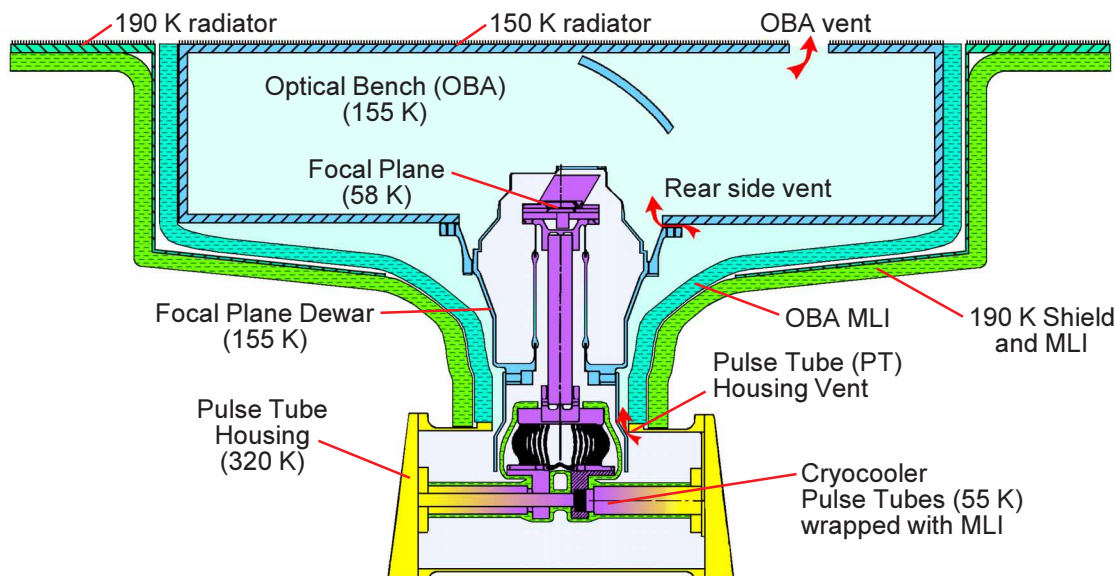


FIGURE 1. Schematic representation of the cryogenic regions of the AIRS instrument.

The cryogenic portions of the instrument are schematically illustrated in FIG. 1. At the top of the figure is the optical bench assembly (OBA) that houses the instrument's spectrometer optics and supports the focal plane dewar. The OBA is passively cooled to ~ 155 K using a 155 K-190 K two-stage cryogenic radiator. The OBA is surrounded by multilayer insulation (MLI) blankets and a 190 K shield that is tied to the 190 K stage of the 2-stage radiator. Below the optical bench is the cryocooler pulse tube housing that supports the pulse tubes of the primary and redundant coolers. This housing is heat sunk to the spacecraft HRS and operates around 320 K when the coolers are operating, and 308 K when they are off.

Extensive characterization of the AIRS cryocooler performance was carried out during the cooler development and qualification testing phases at TRW and JPL [2]. This was followed by extensive characterization of the integrated cooler system at both the instrument and spacecraft level [3].

AIRS INITIAL IN-SPACE PERFORMANCE

The EOS Aqua spacecraft carrying AIRS was successfully launched on May 4, 2002 aboard a Delta II launch vehicle from Vandenberg Air Force Base, California. Following launch, the AIRS instrument was subjected to a 36 day decontamination period to allow time for the high residual moisture in the surrounding spacecraft structure and MLI to dissipate substantially from its as-launched condition. During the first 26 days of this decontamination period, the Earth shield that covered the cryogenic radiators during launch remained closed to maximize the instrument temperature; in addition, a 35-watt decontamination heater was used to heat the OBA to ~ 280 K. On day 26 of the mission, the Earth shield was opened, dropping the OBA temperature to 268 K. To prepare the instrument for operation, the decontamination heater was turned off on day 36, allowing the OBA to reach its controlled set-point temperature of 153 K by day 39.

On day 39, both the primary and redundant (backup) coolers were operated sequentially to verify their health, and the measured cryogenic load was found to be within 25 mW of ground-test predictions [3]. However, soon after, the load began to increase due to contaminants adsorbed onto the instrument's optics and low emittance cryogenic surfaces. Prior to launch it was recognized that periodic decontamination cycles would be required over the life of the mission, and that this need would decrease with time [4]. Once instrument operation began, ice buildup was monitored daily by using the instrument itself to track the loss of IR

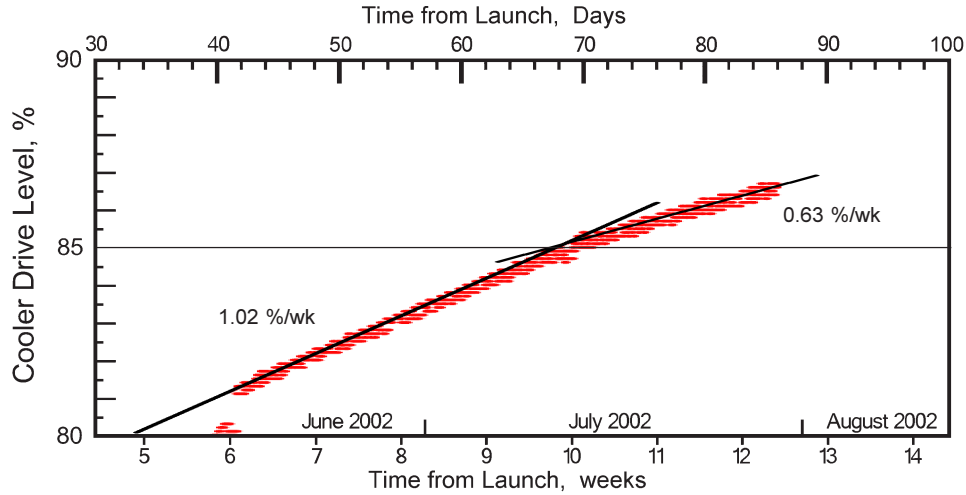


FIGURE 2. Cooler drive increase during the first few weeks of instrument operation.

transmissivity of the instrument's optics within the broad absorption features of water at 4.2 and 10.4 μm . Although IR transmission losses up to 50% can be tolerated in the science data, the cooler drive level was also increasing at a rate near 1%/week as shown in FIG. 2. At initial turn-on, the cooler's drive level was approximately 81%, and the maximum drive limit was conservatively set at 90% to achieve a long operating life. By day 70, the drive level had increased to 85%, with indications that the 90% limit would be reached by day 130. To prepare for the required deicing, a schedule of deicing temperatures and times was prepared. For convenience, the actual process was started on July 29, 2002 (day 86), as the Aqua spacecraft entered into a safe mode on that day, interrupting normal science data.

AIRS DE-ICING EXPERIENCE

Background

To understand the AIRS deicing strategy and results, it is useful to first note the features of the instrument's cryogenic regions that are subject to icing, as schematically illustrated in FIG. 1. From a science perspective, the key elements are the optical surfaces interior to the instrument's 155 K OBA noted at the top of the figure. The interior of this bench is vented to dark space through the entrance aperture and through a 40 mm hole in the instrument's 150 K radiator. Below the optical bench is the cryocooler pulse tube housing, whose only vent path is into the rear of the optical bench, beneath the MLI that surrounds the OBA. This region on the bottom side of the OBA is subsequently vented to the interior of the OBA via small passages around the focal plane dewar mount as noted in the figure.

During operation of the instrument, ice forms in three regions: 1) on the optical surfaces within the OBA, 2) on the rear (outer surfaces) of the OBA, and 3) on the cryogenic pulse tube (PT) surfaces ($\sim 55\text{ K}$) and MLI within the pulse tube housing. The rate of ice accumulation (or loss) is driven by the relative water vapor pressures within these volumes coming from sources of water vapor — the external composite structures and MLI; the vent paths to space are also important. TABLE 1 summarizes the relevant temperatures and pressures for these regions based on the vapor pressure curve for water noted in FIG. 3 [4].

Two key points observable from the table are: 1) that the 155 K optics will only accumulate ice when the water vapor pressure exceeds 10^{-7} torr, and 2) water that freezes on the rear surfaces of the OBA will create a background pressure of 10^{-7} torr on the outside of the pulse tube housing vent. As this water vapor migrates to and enters the PT housing, it will bounce around until it hits the cold pulse tube. At that time it will stick until the PTs are deiced, as at 55 K the effective back pressure from the pulse tube ice is near 10^{-30} torr.

TABLE 1. AIRS cryogenic region temperatures and associated water vapor pressures.

Parameter	Normal Operation	Cooler Off	Decontam. Heaters 'ON'
OBA Temperature	155 K	155 K	268 K
OBA Pressure	10^{-7} torr	10^{-7} torr	5 torr
PT Temperature	55 K	210 K	282 K
PT Housing Pressure	10^{-30} torr	10^{-2} torr	10 torr

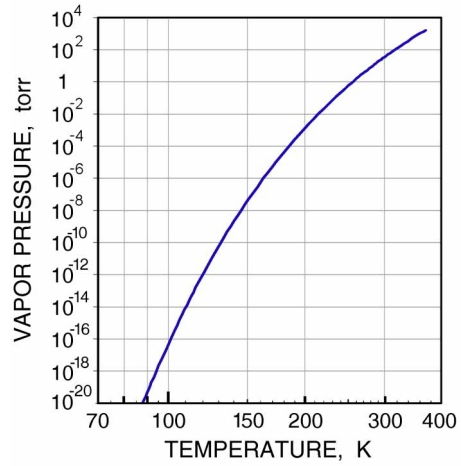


FIGURE 3. Saturation pressure curve for water.

TABLE 1 also indicates that the outgassing pressures when the decontamination heater is turned on are considerably higher than when just the cooler is turned off (seven orders of magnitude for the OBA pressure— and three orders of magnitude for the PT housing pressure). This implies that the outgassing rates when the decontamination heater is turned on should be several orders of magnitude greater than with just the pulse tube cooler turned off.

De-Icing Results

The strategy developed for the deicing involved first turning on the decontamination heaters for several days to dwell at elevated temperatures sufficient to drive out the accumulated water through the OBA space vent. Next, the OBA would be cooled down and allowed to reach equilibrium at 155 K for a day or so prior to starting the cryocooler. This would ensure that the OBA interior water vapor pressure was fully reduced to 10^{-7} torr, the equilibrium water vapor pressure at 155 K, prior to starting the cryocoolers. Last, the cooler would be restarted to bring the focal plane down to its 58 K operating temperature.

The above sequence was started on July 29, 2002, with the turning off of the cryocooler, followed by turning on the decontamination heaters the next day (day 87). After 6 days of deicing, the decontamination heater was turned off (day 93), and the OBA was allowed to cool to its 155 K operating temperature. Because of the spectrometer's large thermal mass, 72 hours are required to passively cool down and stabilize the spectrometer at its proper operating temperature after each defrosting. Unfortunately, this large thermal excursion has a small, but measurable, impact on the instrument's spectral calibration, which necessitates several more days of calibration rechecks and gain adjustments. On day 97 the cooler was restarted and had returned to its original 81% drive level.

Cryocooler Trip Outs

Although the deicing procedure was totally successful, the operating cooler unexpectedly tripped off due to an apparent Watch Dog Timer (WDT) fault after only five hours. Analysis of engineering telemetry showed that the cooler had been operating normally up to the time of the event, indicating that it was a false trip. False WDT trips had also been observed infrequently during earlier instrument ground testing, and the design deficiency associated with the false WDT trips had been identified by the cooler vendor and fixed in subsequent generations of cooler electronics. For AIRS, this was an operational annoyance and not a threat to the flight hardware. Subsequent to the event, a software patch was uploaded to disable the WDT feature in the AIRS cooler electronics. On August 14 (day 102), the cooler was restarted and operated normally for the next eight days.

On August 22 (day 110) a second cryocooler trip-out occurred, this time due to an apparent compressor overstroke incident. At the time of the event, the Aqua Observatory was passing through the South Atlantic Anomaly (SAA), and four days earlier a large Coronal Mass Ejection observed on the sun may have increased the level of energetic protons concentrated in the SAA. As with the previous cryocooler trip-out, the engineering telemetry showed that the cooler had been operating normally up to the moment of the overstroke trip, and there was no indication of an actual piston overstroke condition. Also, the existence of electronic parts in the overstroke circuit that were sensitive to Single Event Transients (SETs) had been previously identified by the cooler vendor (TRW) and replaced in subsequent cooler electronics units. After a thorough investigation, the cryocooler was restarted on August 26 (day 114). It then operated normally for the next 54 days.

On October 19 (day 168) a second cryocooler overstroke trip-out occurred, again while the Aqua Observatory was passing through the South Atlantic Anomaly (SAA). As before, the engineering telemetry showed that the cooler had been operating normally up to the moment of the overstroke trip, and there was no indication of an actual piston overstroke condition. At the time of the SET trip, the cooler stroke had gradually increased from its initial 81% up to a level of 86%, so plans for a second decontamination were in work.

Second Abbreviated Cryocooler Decontamination Procedure

Given that the cryocooler was shut down and that icing had progressed to a fairly high level, this second SET event provided the opportunity to evaluate the benefit of an abbreviated decontamination procedure that would minimize the instrument downtime and not use the decontamination heaters that thermal cycle the optical bench. For the user community, this would minimize the interruption of the baseline atmospheric measurements and make the AIRS data sets more complete.

As noted in the second column of TABLE 1, it was reasoned that the outer surfaces of the 155 K optical bench could be used to cryopump (at 10^{-7} torr) the water vapor from the pulse tubes, which would be at 10^{-2} torr when the pulse tube surfaces reached 210 K. The chief unknown was whether the outgassing pressure at 210 K (10^{-2} torr) would be sufficient to drive the water vapor out of the pulse tube housing through the rather restrictive path to the OBA rear side. If not, the water vapor in the PT housing would quickly re-freeze on the pulse tube MLI surfaces, and the 86% drive level would quickly return. If most of the water vapor could be forced out to the OBA, then the reverse vapor flow should be five orders of magnitude slower (10^{-7} torr driving pressure versus 10^{-2} torr) and good decontamination should be achieved.

After a short, three-day decontamination period, the cooler was restarted on day 170. Immediately after the cooler was started the drive level returned momentarily to 81%, representing a decontaminated cooler. However, within one day, the drive level returned to 85.5%, less than 1% below where it had been prior to the SET trip event. Thus, the abbreviated decontamination was unsuccessful.

IMPLEMENTING A TWO-COOLER OPERATIONAL STRATEGY

Given the likely need for decontamination processes every few months in the future, and the possibility of continued cryocooler trip-outs, a decision was made to thoroughly examine alternative operating procedures that would increase the AIRS instrument science availability and minimize thermal-cycle stressing of the focal plane and OBA. A leading alternative was to run both coolers (the primary and the backup) simultaneously. This had two very positive attributes: 1) The increased capacity of two coolers could accommodate a higher level of icing and thereby lengthen the interval between required decontaminations, and 2) In the event of a cryocooler trip-out, the second cooler could carry the focal plane

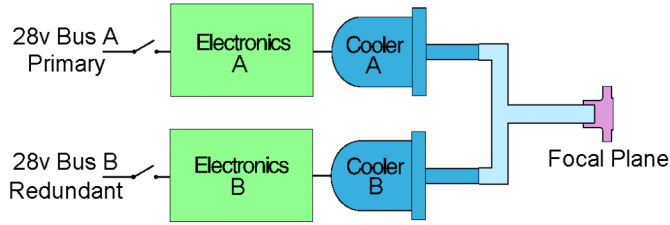


FIGURE 4. AIRS block-redundant cryocooler arrangement.

cooling load at a temperature close to the operational 58 K level, thus minimizing thermal cycling of the focal plane to 210 K each time a cooler tripped off.

From a spacecraft power perspective, the impact of two-cooler operation was expected to be minimal because nearly 50% of the AIRS cooler load is the parasitic load of the non-operating redundant cooler. If the second cooler is turned on, the total cooling load will drop in half and be shared by the two coolers. Thus, with two-cooler operation, each of the operating coolers will only be carrying one quarter of the cryogenic load, and only require a ~62% drive level. When the required spacecraft bus power was computed for the two-cooler operating mode, it was found to be comparable to that for a single cooler.

The primary issue in need of analysis was the extent to which operating both coolers simultaneously might reduce the total AIRS system reliability.

Two-Cooler/Focal Plane Reliability Analysis

Since the early 1990s, the AIRS instrument design was based on block redundant cryocoolers. This redundancy concept, illustrated schematically in FIG. 4, greatly enhances the cooler system reliability as required for the multi-year mission.

Because of the number of cryocooler on-off cycles being experienced during the first few months or the mission, and concerns over their possible impact on instrument operational time and focal plane reliability, a decision was made to revisit the cryocooler reliability trade-off and include in the calculations the reliability of the focal plane and the impact of the operational strategy on instrument calibration and operational availability.

For a redundant cooler system as shown in FIG. 4, the probability of failure in N years is given by:

$$P_{\text{sys}} = N^2 P_A (P_{B1} + P_{B2})/2 + N P_{\text{FP}} \quad (1)$$

where P_{sys} = probability of failure of cooler/focal plane system in N years; P_A = probability of failure/year of cooler A + electronics A, where unit A is the primary unit; P_{B1} = probability of failure/year of cooler B + electronics B during the time before unit A fails; P_{B2} = probability of failure/year of cooler B + electronics B during the time after unit A fails; and P_{FP} = probability of failure of the focal plane.

Because this trade is between a single, heavily loaded cooler and two lightly loaded coolers, an important part of the analysis was estimating the dependency of mechanical cooler and electronics reliability on drive level, and the dependency of focal plane reliability on thermal cycling. To understand the consequences of the assumptions, TABLE 2 was generated with rough estimates for the above probability parameters for the three cooler

TABLE 2. Assumed probability of failure (fraction/year) for cooler system elements and focal plane.

Cooler Drive Level	Focal Plane Thermal Cycling	Cooler Electronics	Mechanical Cooler	Focal Plane
Cooler at 85% drive	extensive	0.01	0.02	0.01
Cooler at 62% drive	minimal	0.0075	0.01	0.005
Cooler unpowered	n/a	0.0025	0.0025	n/a

drive levels of interest. The table reflects a small effect of drive power level on the electronics reliability and a larger effect on the mechanical cooler; it also reflects a small probability of failure assigned for an unpowered unit to account for mechanisms such as long-term creep and internal contamination that are independent of applied power. The next step was to quantify the results of the assumptions, and then to refine the assumptions as required.

Substituting the numbers of TABLE 2 into Eq. 1 for a 5-year operating period gives the following probability of failure estimates for the two cooler-system operational scenarios:

One cooler operating at 85%, one unpowered standby cooler, thermal-cycled FP:

$$\begin{aligned} P_{\text{sys}} &= N^2 P_A (P_{B1} + P_{B2})/2 + N P_{\text{FP}} \\ &= 25 (0.01 + 0.02)[(0.0025 + 0.0025) + (0.01 + 0.02)]/2 + 5 \times 0.01 \\ &= 0.0131 + 0.050 = 0.0631 \end{aligned} \quad (2)$$

Two coolers operating at 62%, one goes to 85% if other fails, FP not thermal-cycled:

$$\begin{aligned} P_{\text{sys}} &= 25 (0.0075 + 0.01)[(0.0075 + 0.01) + (0.01 + 0.02)]/2 + 5 \times 0.005 \\ &= 0.0104 + 0.0250 = 0.0354 \end{aligned} \quad (3)$$

These numbers indicate that focal plane reliability plays a significant role in the computation, and that two lightly-loaded operating coolers may be somewhat more reliable than a single heavily-loaded cooler. Thus, two-cooler operation should be fully considered.

Switchover to Two-Cooler Operation

Based on the above considerations and with the agreement of the Aqua project, a two-cooler operational strategy was implemented on a trial basis on November 21, 2002 (day 201). A key motivator at that time was the need to defer a second decontamination attempt until after the first of the calendar year when there was less of an impact on science operations. Immediately upon switching to two-cooler operation, the drive levels dropped to 61% and 64% for coolers A and B, respectively, as shown in FIG. 5. Over the eight months since the switch to two-cooler operation, the drive level has increased less than 2 percent, the instrument has not been deiced, and no cooler trip-outs have been experienced. The two-cooler operational strategy is now the baseline for the instrument.

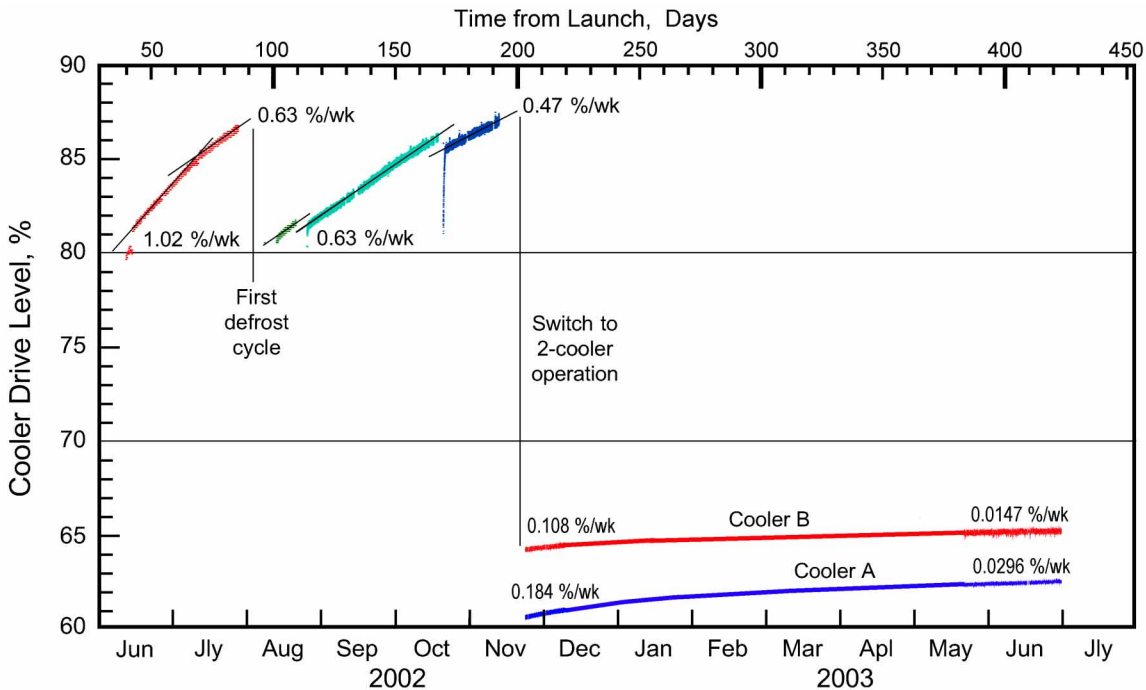


FIGURE 5. Overall summary of AIRS cooler drive level over the first year of operation.

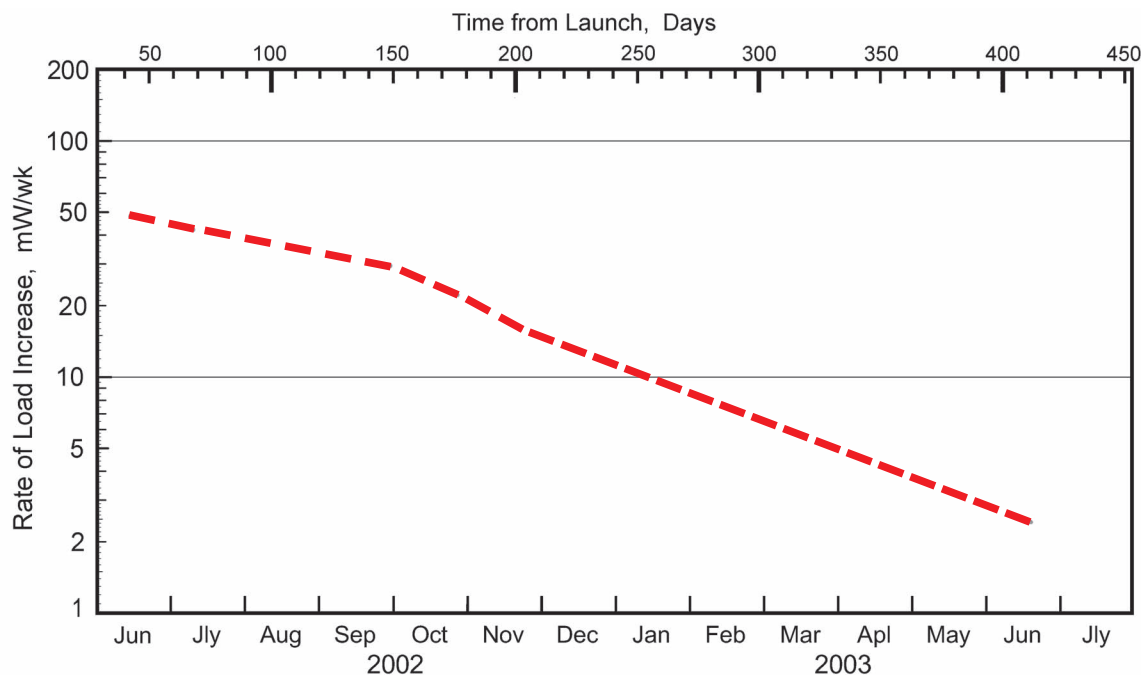


FIGURE 6. Rate of cryogenic load increase for the AIRS instrument over the first year of operation.

COOLER PERFORMANCE SUMMARY

Over the past year the AIRS instrument has performed beyond expectations, with flawless cooler performance since the start of two-cooler operation in November 2002. Also, valuable data have been acquired in the area of on-orbit contamination. With respect to the OBA, its level of icing slowed and eventually stopped in the October 2002 timeframe, indicating that the ambient instrument water vapor pressure fell below 10^{-7} torr near this time. As shown in FIG. 6, the rate of icing of the cooler also decreased over the year, as deduced from the rate of drive increase and the near constant relationship (50 mW/%drive) between load and drive level [3]. Some of this slowing may be saturation of the effect of the ice on surface emittances, as essentially no decontamination has occurred since the thorough August 2002 deicing procedure was conducted. As a result of the current slow rate of cooler drive increase, no further instrument decontaminations are expected to be needed.

ACKNOWLEDGMENT

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